

' N74 30924

Electron Beam Welding of Aircraft Structures

by

R. H. Witt

Grumman Aerospace Corporation

Presented At

Symposium On Welding,

Bonding and Fastening

May 30, 1972

Sponsored By

National Aeronautics And Space Administration

George Washington University

and

American Society For Metals

Williamsburg, Virginia

"Electron Beam Welding Of Aircraft Structures"

By

R.H. Witt

Grumman Aerospace Corporation

Requirements for advanced aircraft have led to more extensive use of titanium alloys and the resultant search for joining processes which can produce lightweight, high-strength airframe structures efficiently. As a result, electron beam (EB) welding has been investigated and found to be particularly suited for certain types of primary structure. For example, Ti-6Al-4V rotor hubs were successfully EB welded for the Cheyenne helicopter several years ago at the Solar Division of International Harvester Company. Production of the vehicle is awaiting the results of trials now in progress. Recently, Grumman selected EB welding as a production method for the F-14A Navy Air Superiority Fighter Aircraft and starting in 1969 established it as a major production process for fabricating titanium components. The following F-14A components are now being EB welded in production and are mainly annealed Ti-6Al-4V except for the upper wing cover which is annealed Ti-6Al-6V-2Sn.

- o F-14A Wing Center Section Box (Figure 1, 22 feet long, 70 butt welds)
- o F-14A Lower and Upper Wing Covers joined to Wing Pivot Fitting Assemblies (Figure 2, two alloys)

Grumman also recently participated in EB welding the first two center wing boxes for the March 2 Messerschmidt Multi-Roll Combat Aircraft (MRCA). Messerschmidt (Munich, Germany) is presently tooling up to employ the method developed for production runs.

In the case of the F-14A, it is estimated that use of EB welding for the Center Wing Box saves over 1500 pounds of titanium per aircraft relative to alternate designs considered. This result fits the stated major theme of this Symposium which is "Achievement of Lighter, More Reliable Joint Systems." The paper will cover Criteria for Selection of Welding Processes, the Grumman EB Welding Facility, Development Work on EB Welding Titanium Alloys, F-14A Production and Sliding Seal Electron Beam (SSEB) Welding.

Criteria For Welding Process Selection

Grumman's decision in 1968 to purchase production EB welding equipment and establish an Electron Beam Welding Center was a significant factor in winning the F-14 program. The decision resulted from a consideration of various processes for production of titanium parts which make up 24 percent by weight of the F-14A airframe structure (Figure 3). The wing structure makes up the majority of the titanium used. Originally two large chambers were purchased and installed and made operational in 1969. The facility was increased to over a 10 million dollar investment in 1971 when a third large chamber was purchased, installed and made operational toward the end of the year. These facilities are discussed further later.

The following is a brief discussion of the primary advantages of EB welding that were particularly important in making this momentous decision which has resulted in establishing the largest known EB welding facility in the free world.

EB welding is defined in the Welding Handbook as "a fusion-joining process in which the workpiece is bombarded with a dense stream of high-velocity electrons, and virtually all of the kinetic energy (energy of motion) of the electrons is transformed into heat on impact." A deep-fused area of high depth-to-width ratio is caused by the electron beam drilling a hole by melting and vaporizing the metal bombarded by the fast-moving (half the speed of light) electrons. As the beam moves along the weld seam, the molten metal flows together by capillary action to form the weld.

Perhaps one can better get an idea of the amount of heat generated by a stream of electrons by thinking of an x-ray tube in which a tungsten or molybdenum target is bombarded by electrons to produce x-rays. In many x-ray tubes, water or oil is circulated in the interior of the hollow anode to cool the target. Sometimes, metal fins are adequate to dissipate heat to the air by convection. When the rating of the tube is exceeded or the fluid supply is cut off, however, the target invariably melts.

The amount of heat generated in an x-ray tube operating at a potential difference of 100 KV with a power input of 0.5 KW will heat the anode to 1800°C (3272°F) in one minute of operation. This would result in melting steel or titanium in that amount of time with an unfocused electron beam.

The period of time to melt such materials can be shortened significantly if the electron beam is focused to a smaller spot resulting in a smaller diameter, higher energy density spot and the resultant drilling action of the electron beam mentioned above. This is essentially what happens in an electron beam welding gun to produce continuous welds at high speed. Simple calculations of heat input and theoretical temperature rise using very conservative estimates of beam spot diameter show that temperatures greater than 8000^oF per second are readily produced using between 20-30 KW of power input.

The above considerations indicate why simple butt welds in titanium considerably greater than 0.125 inch thick can be readily produced by EB welding in contrast to most arc welding processes where 0.125 inch is the limit for single-pass welding. This is depicted rather strikingly in Figure 4 where the two-inch-thick GTA weld shown required over fifty weld passes to complete and a V-groove had to be machined in order to deposit filler metal in the joint to obtain full penetration levels. The narrow EB weld shown in Figure 4 was made in the same thickness of Ti-6Al-4V with no groove machined in the simple square butt joint prior to welding; no filler metal was required either. Excessive distortion and hardness increases were noted in the GTA weld whereas the EB weld showed no distortion, less shrinkage across the weld and uniform hardness with no hardening.

Electron beam welding, then, is essentially a mechanized fusion welding process performed in a vacuum chamber where the pressure is reduced to 1×10^{-4} torr or less. Electrons emitted from a filament (Ta or W) are focused and accelerated by an EB gun equipped with a focusing coil and applied potential difference. The stream of high-velocity electrons strikes the workpiece and heat is generated producing welds as described above. Welds can be made with the gun positioned at any angle -- horizontal, vertical or oblique. The gun and/or workpiece move during the welding operation and joints from foil thicknesses up to three inches can be butt welded in a single pass.

Before choosing electron beam welding as the process for the F-14A, gas-tungsten-arc and plasma-arc welding were also considered as potential candidates. All three processes provide equivalent tensile joint efficiencies, but EB welding is the only one that provides almost 100 percent joint efficiency in fatigue for annealed Ti-6Al-4V titanium alloy weldments having thicknesses between 3/8 inch and 2 1/4 inches as per F-14A requirements. Figure 5 presents

EB and GTA welding fatigue data which shows that EB welding is superior in fatigue when reinforcement is removed by machining. Later work on plasma-arc welds also showed fatigue improvement over GTA welds, but this process has a limit of single-pass welding efficiently up to 3/8 to 1/2 inch thickness at best. These facts, coupled with the fact that inert gas shielding is not always effective in making long welds in titanium and contamination (e.g., alpha case) can readily occur, weighed the selection strongly toward the EB welding process. Gas shielding and welding in corners of a wing box are not considered to be easily accomplished consistently with high quality either. The following summarizes major considerations of advantages that EB welding offers at this time for fabricating airframe structures:

- Narrow weld bead (single pass)
- High depth-to-width ratio (can be varied to optimum)
- Small heat-affected zone (HAZ)
- Grain growth minimized
- Extremely pure atmosphere - no contamination (orders of magnitude better than base metal vacuum melting conditions)
- Shrinkage and distortion control excellent
- Static and dynamic mechanical weld properties improved (joint efficiency near 100%)
- Minimized or no machining of weld grooves
- Thicknesses from foil gages to plate weldable with same gun
- High welding speeds from 20 ipm to over 100 ipm available
- Welding operation is mechanized

Of course, there are two sides to every coin and EB welding is no exception. Before making the decision to use this process, it was necessary to determine that the application was still justifiable despite the following potential limitations:

- High initial cost of equipment
- Defects can occur, e.g., arc-outs, cold shuts, lack of fusion . . .
- Precise fitup is required with small diameter (less than 0.1 inch) electron beam, which can result in machining problems especially for long welds
- Difficult-to-weld materials with high vapor pressure
- Vacuum chamber required limits part size

- Magnetic materials can deflect the electron beam
- X-rays are generated above 35 Kv accelerating voltage
- Vapors deposit on optical reflecting and refracting surfaces (mirrors, lens, etc.)
- Repairs costly, if parts must be refixed in the chamber

After considering the above, it was still justifiable to use EB welding to obtain significant weight savings on the F-14A center wing box. This is part of the reason for the F-14A being one of the few modern aircraft to be built in such a short time and still not overrun initial weight predictions-- a fact that is not too often mentioned in the media.

Grumman EB Welding Facility

When one considers the types of electron beam welding equipment that has been marketed, it has been the general rule to classify them as low, medium, and high-voltage types. Basically, the three classes of machines give the following power rating ranges:

<u>Type</u>	Max. Accelerating Voltage, kv	Max. Beam Current, ma	Beam Power, kw
Low Voltage	30	500-1000	15-30
Medium Voltage	60	500-1000	30-60
High	150	100	2-15

Below is a checklist of requirements that are considered to be desirable in the airframe industry, and the general rating for each type of machine is included. From this comparison, it is fairly obvious why the medium voltage type of machine is presently considered to have the edge.

<u>Machine Requirement</u>	<u>Low Volt.</u>	<u>Medium Volt.</u>	<u>High Volt.</u>
Weld 2 1/2 in. Thick Ti and Steel	No	Yes	Yes
Movable Gun (Inside Chamber)	Yes	Yes	No
Regular Bead Widths For Airframe Tolerances	Yes	Yes	?
Beam Deflection Available	Yes	Yes	Yes
Beam Oscillation Available	Yes	Yes	Yes
Automatic Seam Tracking	Yes	Yes	Yes
Short Pump Down Time To 1x10 ⁻⁴ Torr	Yes	Yes	Yes
Size of Chamber	Part Size	Part Size	2x Part Size*
Wire Feed	Yes	Yes	Possible

*Depends on Length of Weld Joint

A primary requirement for making a part such as the center wing box is to have a movable gun which will keep the size of the chamber at a minimum. With a stationary EB gun, the 22-foot-long wing box would require a chamber about 35 feet long by 25 feet wide or more. With a movable EB gun, welding is presently accomplished in a chamber approximately 25 feet long by 9 feet wide. Therefore, medium voltage equipment was selected by Grumman in 1968 when the decision to use EB welding was originally made.

Essentially, three generations of EB guns for medium voltage equipment have been produced and it is noteworthy that each generation has different welding characteristics. Inclusion of TV camera optics in the EB gun body has influenced the beam character significantly in the latest production equipment produced since 1968. The first two generations of guns were produced from 1959 - 1968 and were primarily used in R&D or limited production work. The third generation is typified by the machines that are installed in the Grumman Electron Beam Welding Facility, Bethpage, N.Y., the largest facility of this kind in the world that is actually in production. Figure 6 shows the layout of the self-contained production facility which includes controlled areas for welding, quality assurance, machining, heat treating, chemical cleaning, and forming operations.

Grumman placed an order for two of the largest EB production welding chambers in existence in 1968. They were installed in 1969 and have been in production since late 1969. These machines were considered necessary because new airframe designs in titanium alloys call for large parts and more operational flexibility than is available with most existing equipment. One machine is designed as a "clam-shell" type and is 388 inches long, 126 inches wide, and 96 inches high with 360 degree accessibility to the mechanisms and fixturing (Figure 7). The bed plate carries all the tooling and pumping equipment. The shell can be opened in clam-shell fashion to completely expose the fixturing. All fixturing, checking, etc., can be accomplished in place. One of the other chambers, called a "tunnel" type, has a rectangular cross-section 108 inches wide by 132 inches high with a length of 302 inches (Figure 8). Two end-opening doors permit tooling on tracks to be passed through the chamber for in-line production with multiple tools. A third chamber of the tunnel type was installed late in 1971. The chamber size is 362 x 108 x 132 inches.

Each chamber is provided with gantry mechanisms that give degrees of freedom for the electron beam gun: X, Y, Z, A, and B. Gun mobility is controlled by servo systems. The linear motions available for each machine (Figures 9 and 10) are:

<u>Axis</u>	<u>Clam-Shell Machine</u>	<u>Tunnel #1 Machine</u>	<u>Tunnel #2 Machine</u>
X	310"	248"	315"
Y	82"	70"	70"
Z	12"	54"	53"

With the flexibility provided by these machines, long assemblies of various heights can be welded. Types of parts that can be considered are wing panels, box sections and wing spars. Both of these machines are designed to pump to the vacuum level required ($< 1 \times 10^{-4}$ torr) in less than 20 minutes. Welding speeds of up to 100 inches per minute are available. The electron gun is rated at 30 kw (60 kv @ 500 ma) for each machine. Designs of the gantries allow the addition of another gun in each chamber, if required. Other features of the equipment include magnetic beam focusing, beam oscillation, beam deflection, and a closed circuit TV system for viewing

and locating the weld joint. A digital readout device informs the operator of the exact location of the gun at all times. Automatic wire feeder and seam tracking mechanisms are also available.

Development Work on Titanium

A large amount of electron-beam welding test work has been completed during the past five years at Grumman. A small EB welding chamber (54" x 50" x 54") was used for most of the early work since 1967. In the titanium field, we have EB welded commercially pure titanium, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-8Al-1Mo-1V, Ti-6Al-2Cb-1Ta-8Mo, and Ti-5Al-2.5V. Until recently, it was thought that the most difficult to weld of the titanium alloys was Ti-6Al-6V-2Sn. Although the welds looked good visually, low ductility and fatigue properties limited the use of this alloy for EB welding, particularly in thin gages. Work at Grumman on heavier gages (around 0.5-inch thick) has indicated that weld-line microporosity sometimes caused reduced fatigue properties in this alloy. To eliminate this tendency, it was necessary to employ acid (HNO_3 -HF) cleaning consistently as per GSS Specification #7015, Method 3. Proper postweld stress-relief at 1250°F for four hours has also produced ductility and adequate fatigue and fracture toughness for future design considerations.

Butt weld parameters have been developed for Ti-6Al-4V titanium alloy for many thicknesses over the range of 0.16 inch through 2.0 inches. Tensile, fatigue, flaw growth, and fracture toughness tests have been conducted on 1/4, 1/2, and 1-inch welded plate. The electron beam welding program includes welds prepared with and without the use of filler wire, as well as single and multiple pass welds. In all cases, the static weld joint efficiency has been 100%. While this is an indication of high quality welding, it is not meant to infer that designs are based on full properties in the weld. Hundreds of mechanical tests on electron beam welds have been performed.

Specimen testing has been supplemented by testing of prototype components. Two 50-inch-long specimens, simulating welded longerons or stiffened wing skin designs, have successfully passed a modified 12,000-flight-hour spectrum-fatigue test with the weld bead intact. A Ti-6Al-4V diagonal tension beam (Figure 12) have also been electron beam welded. The diagonal tension beam specimen employed relatively light gage materials in the range of 0.16 inch in thickness, and was about 2 ft x 4 ft in size. The 250-pound carry-through structure employed heavier material (up to 1-7/8 thick) and measured 12 x 14 x 52 inches.

A 1-7/8-inch-thick, electron beam weld was designed to carry primary tension loads. This weld joined a beta-processed plate to a press diffusion bonded laminate and was machined flush. The simulated wing center box structure successfully completed a 12,000-hour spectrum without failure. The initial net stress was set at 80,000 psi for 120 blocks. Each block, representing 100-hour life, consisted of the following:

<u>No. of Load Applications</u>	<u>Load (% of Limit)</u>	<u>Nominal Stress (ksi)</u>
330	69	55.2
110	84.5	69.6
28	100	80
6	115	92

The test was continued after increasing the limit stress to 90,000 psi. At this stress level the failure occurred in the base metal after 24 blocks.

EB studies were also conducted as a part of the beta forging and precision forging evaluation programs. Two forgings were joined at an end flange to form a center rib as shown in Figure 13. F-14 spectrum fatigue testing of this item was satisfactorily completed. This development contributed to the diversification and optimization of the designs for rib and frame structures on the F-14.

F-14 Production

Experience with F-14A EB welding includes design, fabrication and successful static and flight testing of an all-welded center wing box and outer wing covers EB welded to the required pivot fittings. All of the material is annealed Ti-6Al-4V plate and forgings except for the upper wing cover/pivot assembly which is annealed Ti-6Al-6V-2Sn alloy.

As a result of the successful fabrication and test evaluation of the electron beam welded torque box, a full-scale box was designed for the F-14. Figure 14 shows the weld land configuration that was used to weld the straight butt welds (89 in number when the first boxes were fabricated). Extensive test work showed that by using scribed witness lines on top and root-side of each joint, missed joints and other defects could be readily identified, even prior to radiographic examination. Other efforts were directed toward parametric studies on various gages to establish optimum

weld bead shapes and widths. A relatively parallel-sided weld of uniform width was developed. Minimum weld widths of 0.070 - 0.080 inch were made to assure that internal missed seams were not encountered in production welding. The witness lines on top and root side of the weld help to locate the position of the weld bead relative to the original joint. It is required that at least 0.015 inch of weld be measurable on each side of the joint for acceptance.

The results of fatigue and fracture toughness tests were established to finalize the design of the box. Reweld studies were accomplished to determine the effect of rewelding on mechanical properties as well. It was found that seven rewelds were not detrimental so that various defects can be EB repaired. The fatigue studies showed that fatigue properties were reduced by leaving the weld reinforcement intact or by eliminating stress relief after welding. Essentially 100% fatigue efficiency is obtained when reinforcement is removed and a stress relief at 1200°F for 4 hours is utilized after welding. Lower stress relief temperatures reduce efficiency. Fracture toughness requirements call for a K_{IC} of 70.0 for base metal and a minimum of 37.5 for electron beam welded plate. Fatigue flaw growth tests were also run to establish critical flaw sizes for twice the spectrum fatigue life of the aircraft.

The center wing box is essentially manufactured in modular construction from four basic boxes (Figure 15). Starting at the left end of the box, there is a L.H. outboard module, L.H. inboard module, R.H. inboard module and R.H. outboard module. Each module is initially fabricated from its own bottom plate, side plates, end plates and rib stiffeners. The top of the box is welded on last, so that initial module joining includes inboard-to-outboard modules. The left side of the box is then joined to the right side at the midpoint transverse centerline. The top covers are then sequentially installed. Since forgings have become available, the number of welds have been reduced to 70. Of these, 52 welds are greater than one-inch thick and eight are greater than 1.9-inch thick. The smallest gage is 0.580-inch thick. It takes 25 setups to fabricate each wing center-section. All electron beam welds employ start and stop tabs integrally attached to the part, where possible, to avoid defects associated with starting and stopping of the weld. Integral tabs are essential, particularly

for deep welds, to assure proper solidification and prevention of bursts near the finish-end of the welds.

The operational sequence for production weldments is:

- | | |
|----------------------------|---------------------------|
| 1. Prefit | 9. X-ray inspection |
| 2. Apply witness lines | 10. Ultrasonic inspection |
| 3. Clean | 11. Clean |
| 4. Setup | 12. Stress relieve |
| 5. EB weld | 13. Descale |
| 6. Visual inspection | 14. Penetrant inspection |
| 7. Witness line inspection | 15. Clean |
| 8. Machine weld | |

Upper and lower wing covers are fabricated using essentially the same procedures. However, the wing plank is hot formed to a moderate curvature prior to welding. The initial weld in a typical wing cover is a relatively short one joining the pivot section to an actuator piece on the inboard wing cover (Figure 2). After removal of end tabs and final machining, the inboard cover is welded to the outboard cover. Figure 16 shows this weld being made and the related tooling required.

To date over 30 wing center boxes and many sets of wing covers have been EB welded and accepted by quality assurance for flight and test articles.

Sliding Seal Electron Beam (SSEB) Welding

An Air Force-sponsored program (Contract F33(615)-70-C-1806) at Grumman is directed toward generation of performance data, determination of the functional capability of a Government-owned SSEB welding system, and demonstration of a capability to weld large aerospace structures (Figure 17).

This program commenced in August 1970 and will be completed this year. Straight butt welds in the downhand position have been produced in annealed Ti-6Al-4V and 2014-T6 aluminum alloys for thicknesses up to one inch thick and HY-130 steel up to 1/2 inch thick. Some bead-on-plate welds have demonstrated capability to weld two-inch-thick aluminum and 1 1/2-inch-thick titanium for lengths up to two feet. On the basis of power input, it is probably possible to weld 1/2 to one inch additional thickness with this equipment. F. R. Miller of AFML is the Air Force Manager for this program.

To make an SSEB weld at the present time, it is first required to make a GTA seal-pass weld approximately 0.050 inch deep to prevent vacuum leakage when SSEB welding. Following this, the part is immediately transferred to the SSEB welding fixture which has double O-ring seals (Figure 18). The backing pump is turned on and the small backup chamber pumped to below 50 microns of mercury. The welding head equipped with double-ring seals (Figure 19) is positioned on top of the GTA sealed weld plate and pumped down to a vacuum around one micron of mercury. The weld is then made with a full-penetration SSEB weld pass. Figure 20 shows typical microstructures of SSEB welds in various thicknesses of Ti-6Al-4V up to one inch thick. The higher pressure of the SSEB vacuum compared to the chamber "hard vacuum" appears to result in less spatter and generally smoother underbead configurations.

SSEB welded tensile properties are summarized in Table I together with weld parameters employed for weldments 1/4 to one inch thick. The parameters including welding speed are similar to those used in "hard vacuum" chambers for the same gages of material and near 100% tensile joint efficiencies and good elongation are obtained. Unnotched fatigue efficiencies of 100% were obtained at a stress ratio of +0.1 and fracture toughness (K_{IC}) of 39.0 for SSEB resulted with plate having K_{IC} of 55.4.

The final phase of the program is an evaluation of SSEB butt welding as it might be used to manufacture a simulated stiffened titanium wing skin for an aerospace structure. Figure 21 shows a section of an SSEB welded panel with the SSEB weld transverse to the length of the panel. A fatigue test specimen machined from the weldment is also shown in the figure. This weld was made by building up the weld area as indicated in Figure 22 using titanium rib blocks to produce a constant weld depth. These blocks were machined out after welding. The panels are now being spectrum fatigue tested.

Such a structure might be employed in producing wing planks for future aerospace vehicles where parts are too large to be welded in existing EB chambers. These parts might run from 35 to 70 feet in length or more. Usually it is proposed to EB weld such a structure by joining narrow, stiffened extruded sections longitudinally parallel to the stiffeners along the length of the skin. Such an approach would not be economically practical at this time for the following reasons:

Long length (20 to 50 feet) welds in multiple stringers would require costly machining and fitup practices, inspection of long lengths of weld, and would be difficult to repair. If, for example, ten stiffeners were required per plank, 200-500 feet of joint would have to be machined, fitted-up carefully and ultimately inspected by radiography and ultrasonics. Using transverse weldments, it is possible to keep the total weld length down to 15 to 30 feet per plank, resulting in much less cost and time.

Depending on the ultimate design of the stiffeners and the weld location, it may not at all be possible to apply SSEB welding to longitudinal joints. Also, the present equipment has a maximum stroke of six feet when the gun is moved in the downhand position and five feet in the vertical position. This makes it mandatory to move the part which has not been developed for this equipment to date.

Another area in which the SSEB welding process may be readily adaptable is in welding large cylinders and tankage. However, considerable development will be required before such uses become practical. Any weldment that would require post-heat-treatment (e.g., solutioning, annealing and stress relieving) first requires that large heat-treat facilities be made available to handle 20 to 40-foot-diameter tanks.

Conclusions

From the foregoing discussion it is evident that EB production welding has come a long way since the early 60's. To one who has been involved in EB welding in the aerospace industry since 1958, it is with great satisfaction that these results can now be presented.

The future of electron beam welding such reactive alloys as titanium is very promising. As designers and stress people get more familiar with the structural efficiencies attainable in strength and weight savings, other companies and industries will invest in EB welding equipment for primary structures. Coincident with the development of large vacuum chambers with movable EB guns and large, precision tooling, non-destructive inspection methods have been improved to the extent that quality can be consistently controlled even in deep structural welds. Further development of out-of-chamber methods such as SSEB welding should enhance versatility and extend potential application areas to larger parts than can now be efficiently welded.

TABLE I

ANNEALED Ti-6Al-4V WELDED TENSILE PROPERTIES

THICK., IN.	UTS/JE*	YS/JE*	ELONG/JE*
1/4	143.2/ 99.6	138.3/ 98.2	9.7/80.7
1/2 Trans	138.5/100.0	134.1/ 99.7	11.8/87.5
1/2 Long.	144.9/105.3	140.7/102.8	12.3/80.6
3/4	139.5/101.2	138.0/101.9	10.3/77.5
1 Trans	159.1/113.5	146.4/107.9	9.3/66.4
1 Long	144.1/ 99.2	137.7/ 97.2	11.0/82.7

THICK., IN.	BEAM VOLT., KV	BEAM CURR, MA	WELDING SPEED, IPM	HEAT INPUT, KJ/IN.
1/4	40	180	60	7.2
1/2	45	270	50	14.6
3/4	50	300	50	18.0
1	50	330	45	22.0

* UTS - Ultimate Tensile Strength
 YS - Yield Tensile Strength
 ELONG-Elongation
 JE - Joint Efficiency

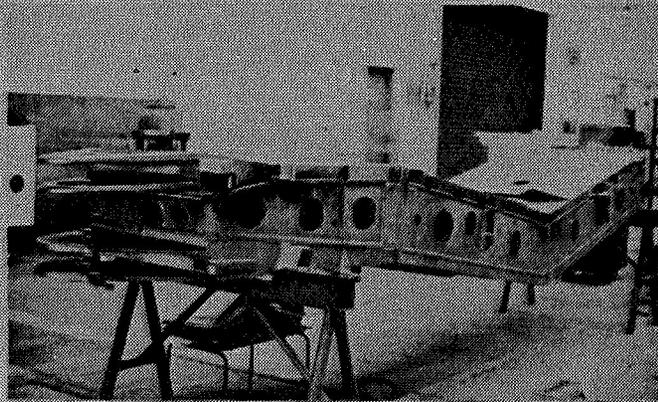


Figure 1. F-14A Wing Center Section Box

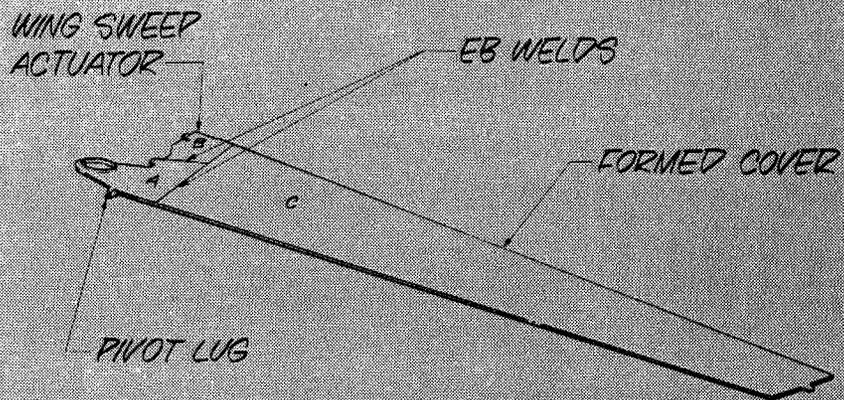


Fig. 2 F-14A Wing Outer Panel

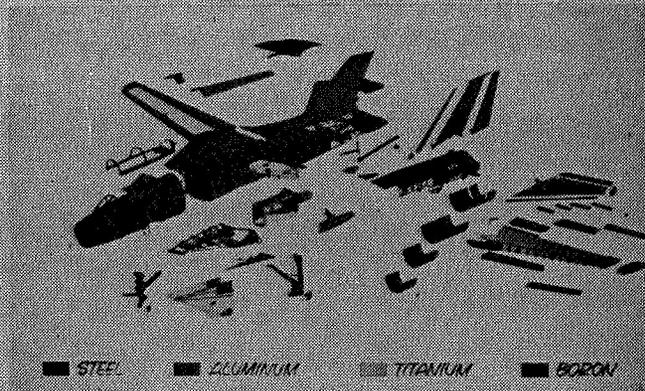
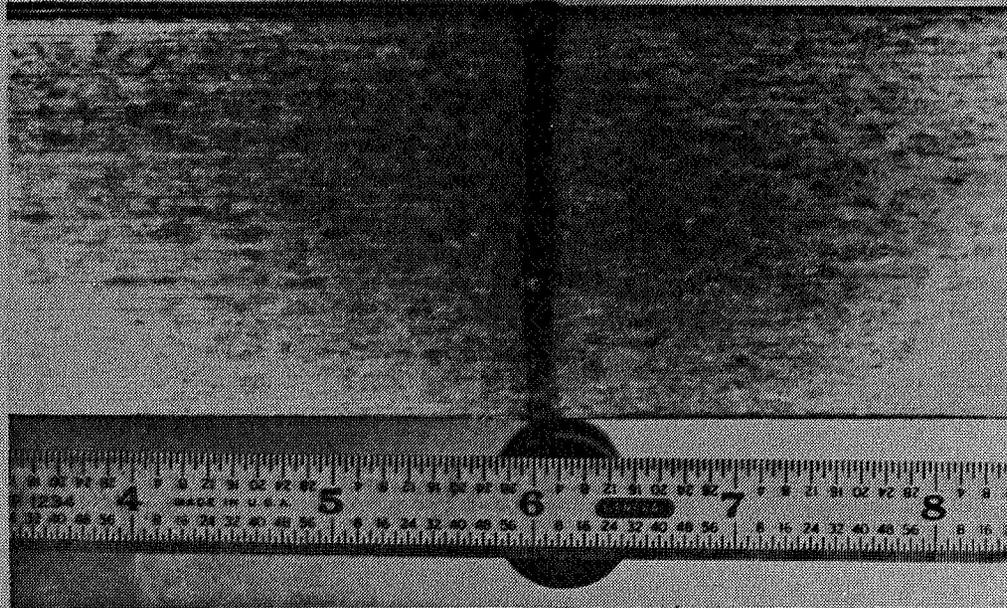
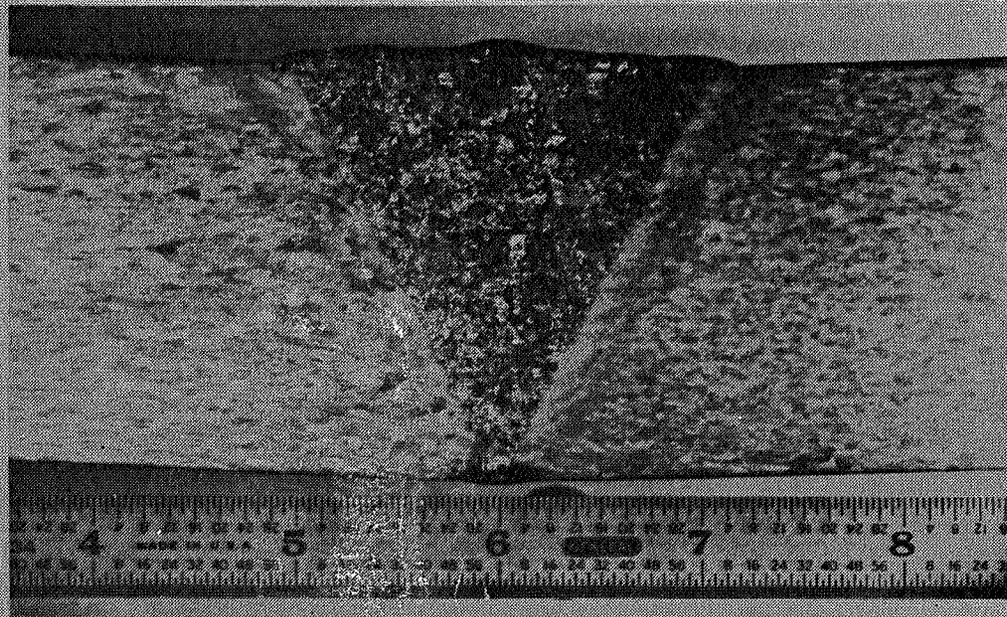


Figure 3. F-14A Structural Components



a. EB Weld



b. GTA Weld

Figure 4. Welds in Two-Inch-Thick Ti-6Al-4V Titanium Alloy Plate (1.3X MAG)

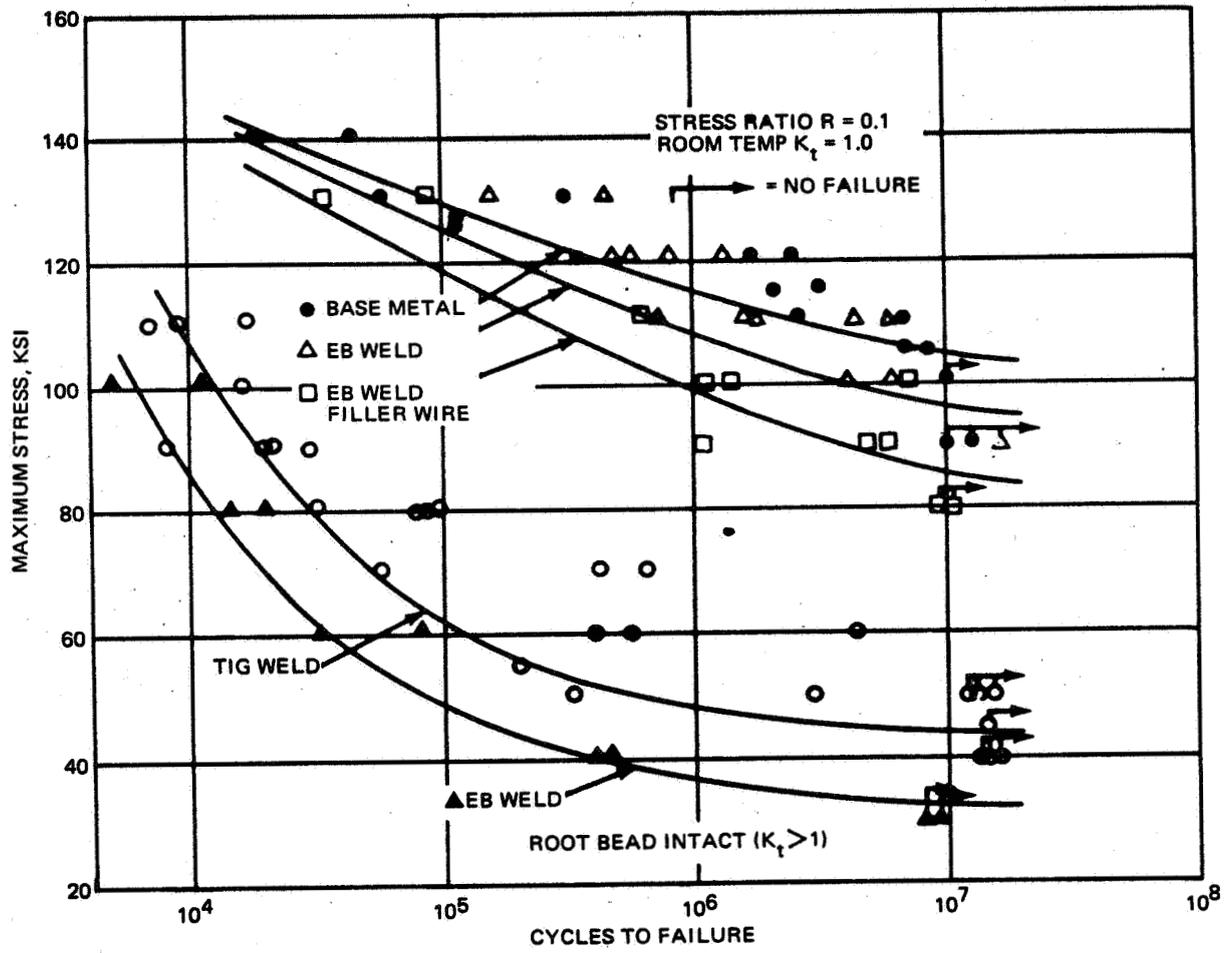


Figure 5. EB and GTA Fatigue Data

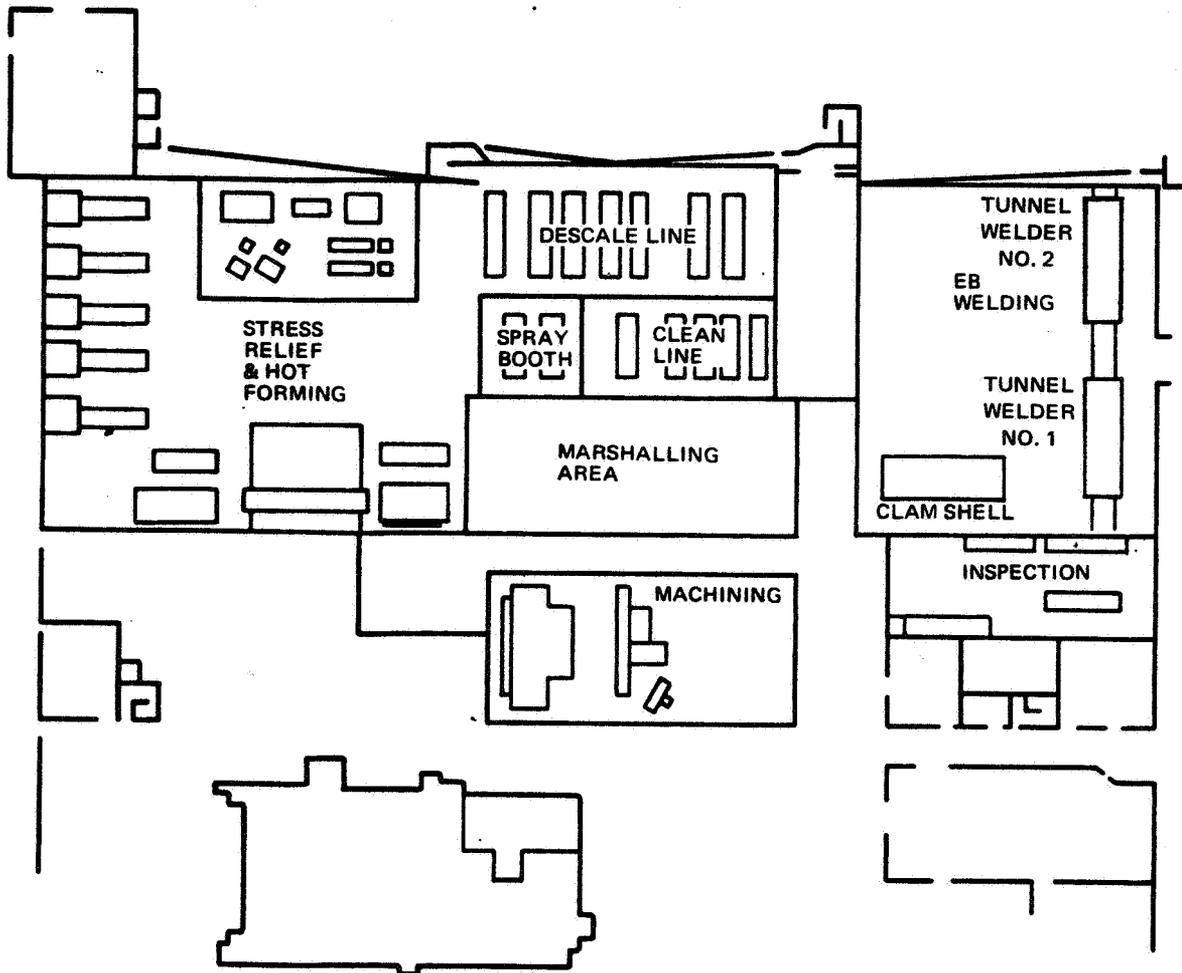


Figure 6 Electron Beam Welding and Related Facilities - Plant 2

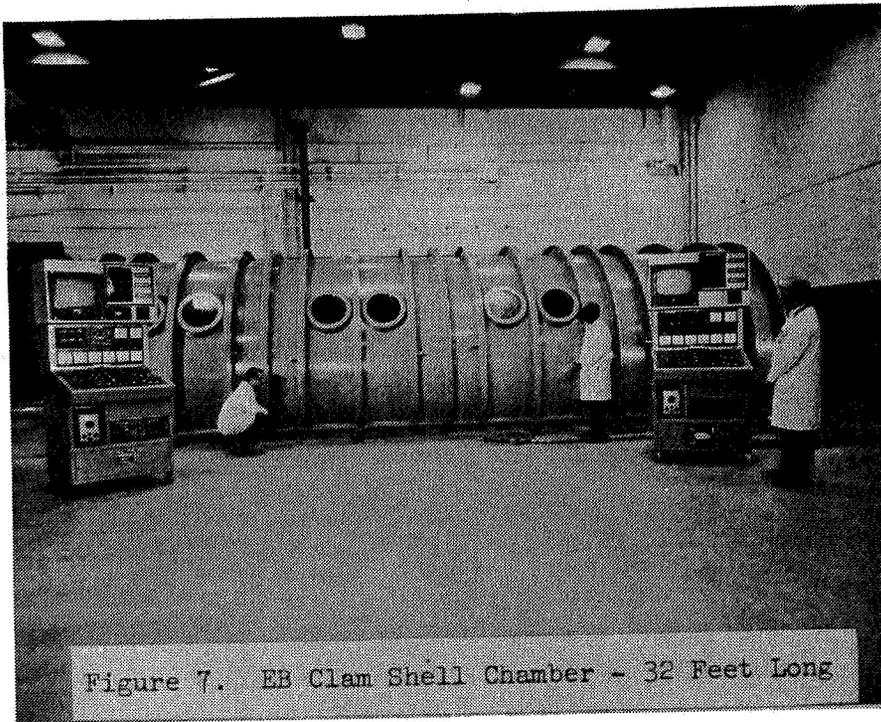


Figure 7. EB Clam Shell Chamber - 32 Feet Long

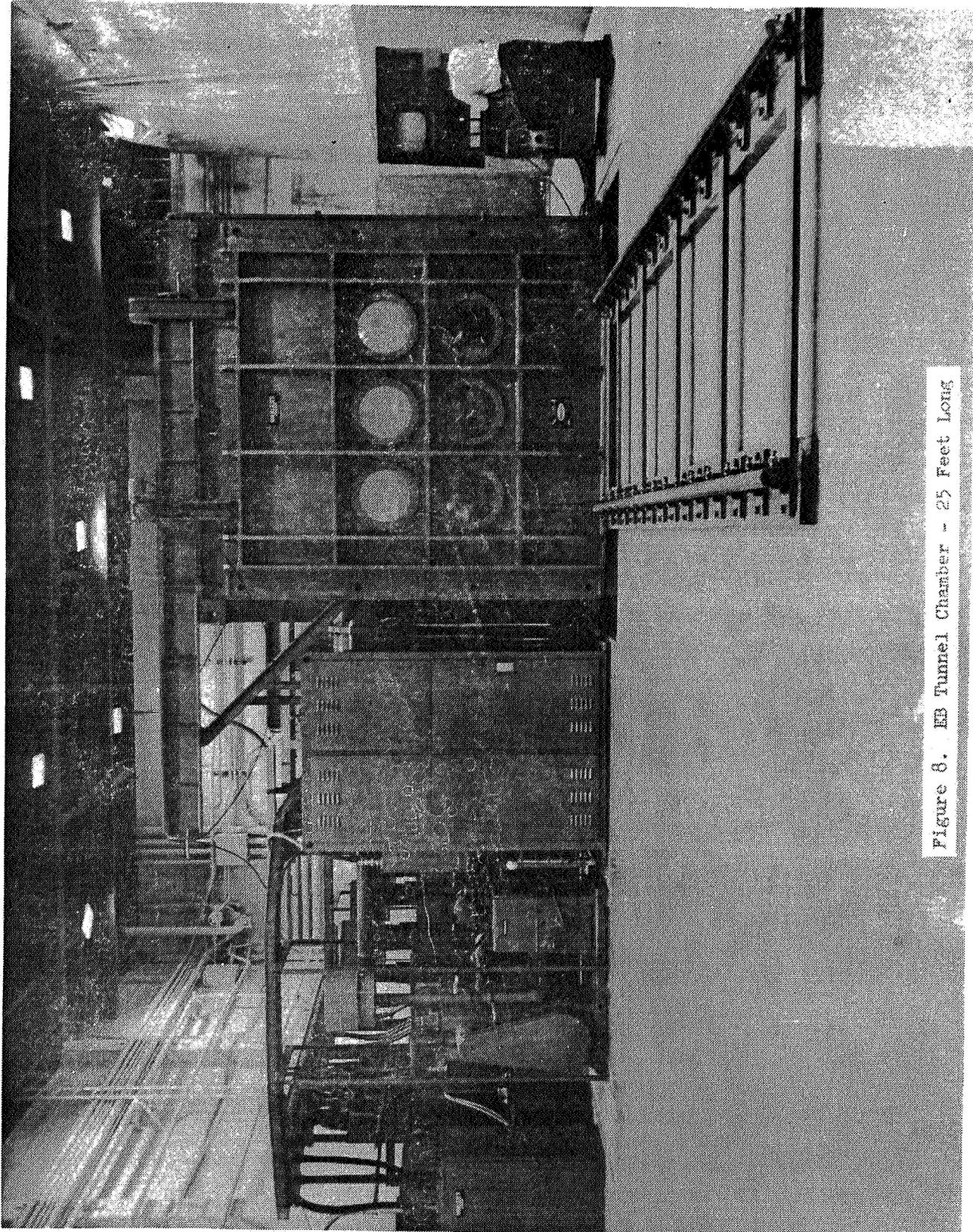


Figure 8. EB Tunnel Chamber - 25 Feet Long

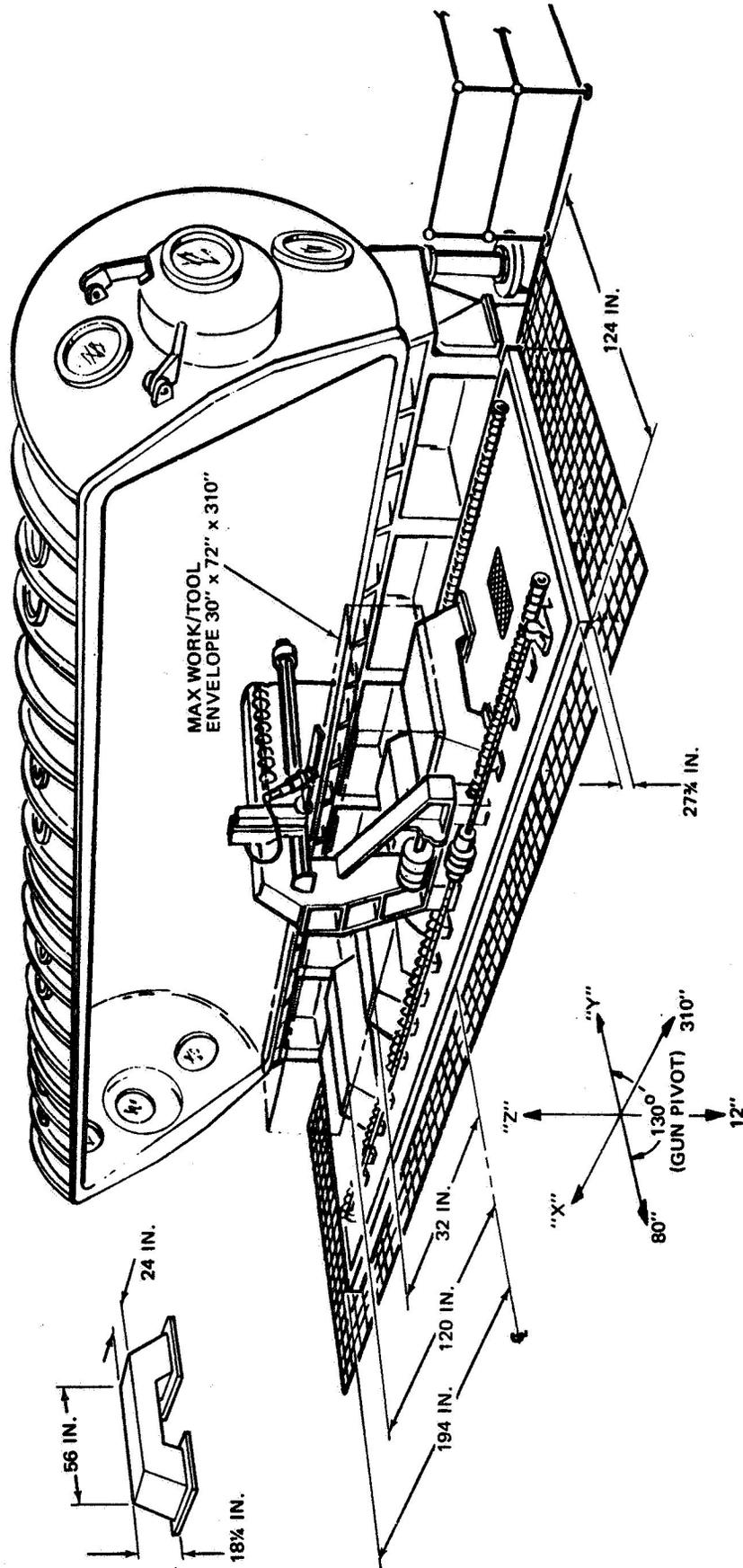


Figure 9 EB Clam-Shell Chamber - 388 x 124 x 96 Inches

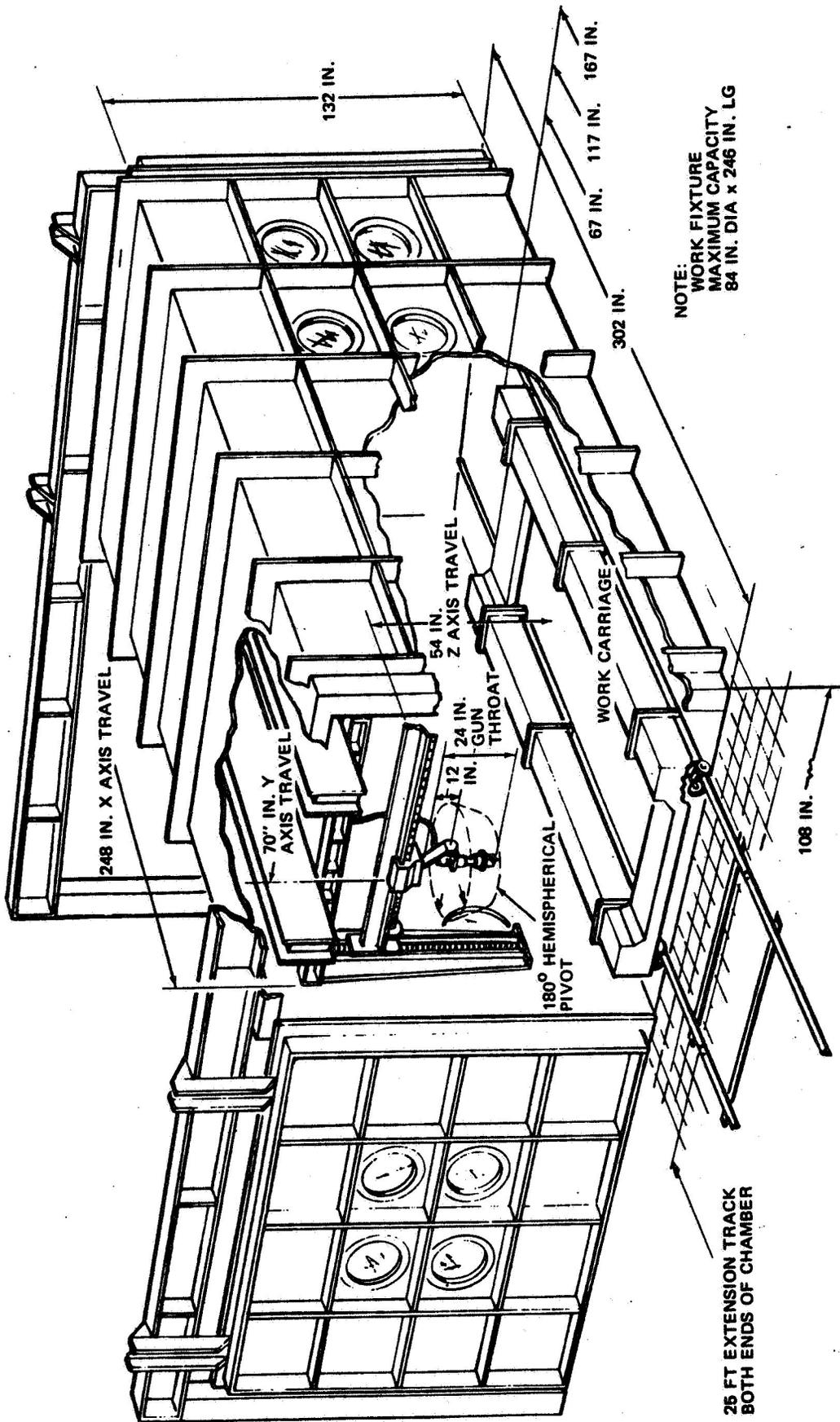


Figure 10 Rectangular EB Chamber - 302 x 108 x 132 Inches



Figure 11. Ti-6Al-4V EB Welded Diagonal Tension Beam

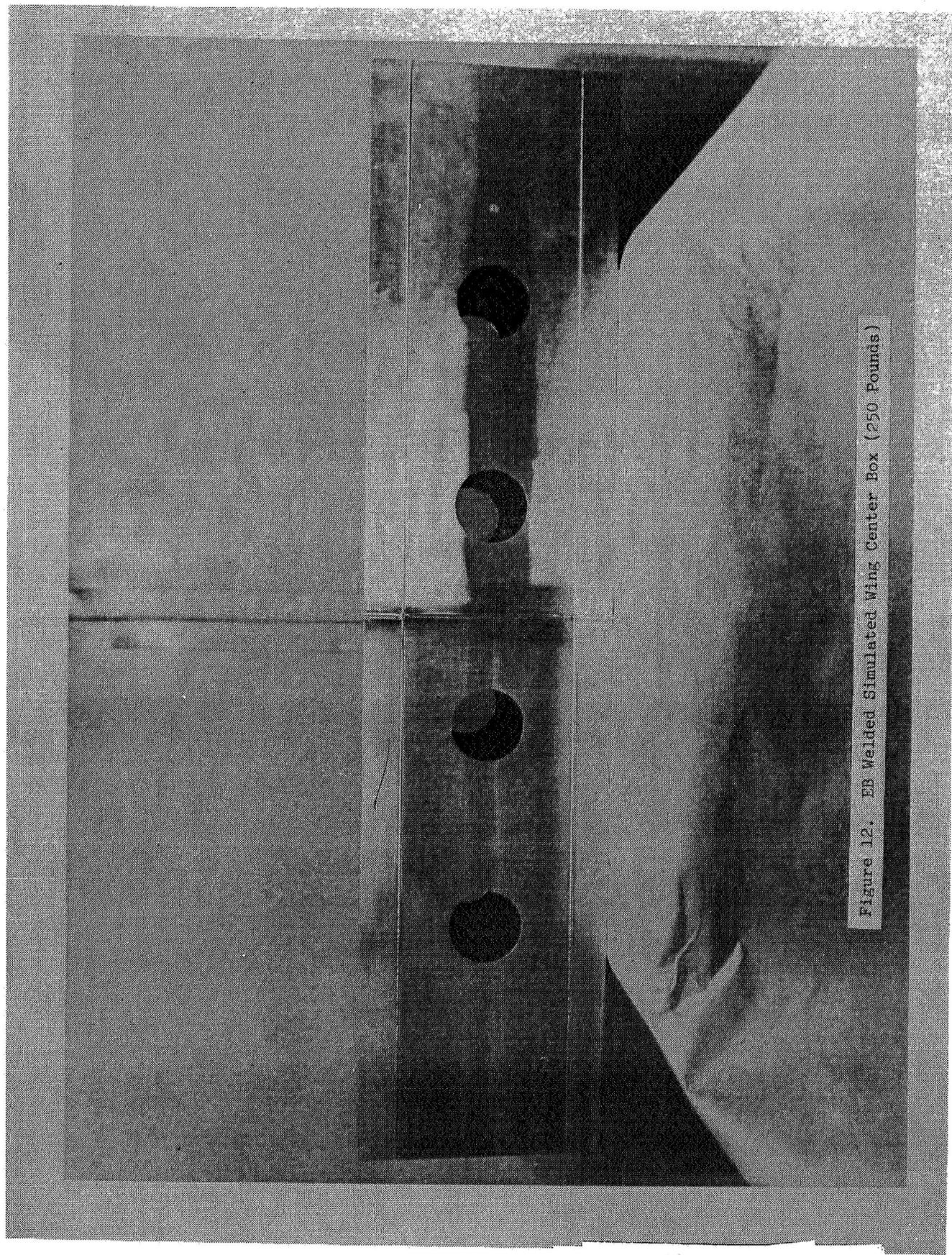


Figure 12. EB Welded Simulated Wing Center Box (250 Pounds)

51a

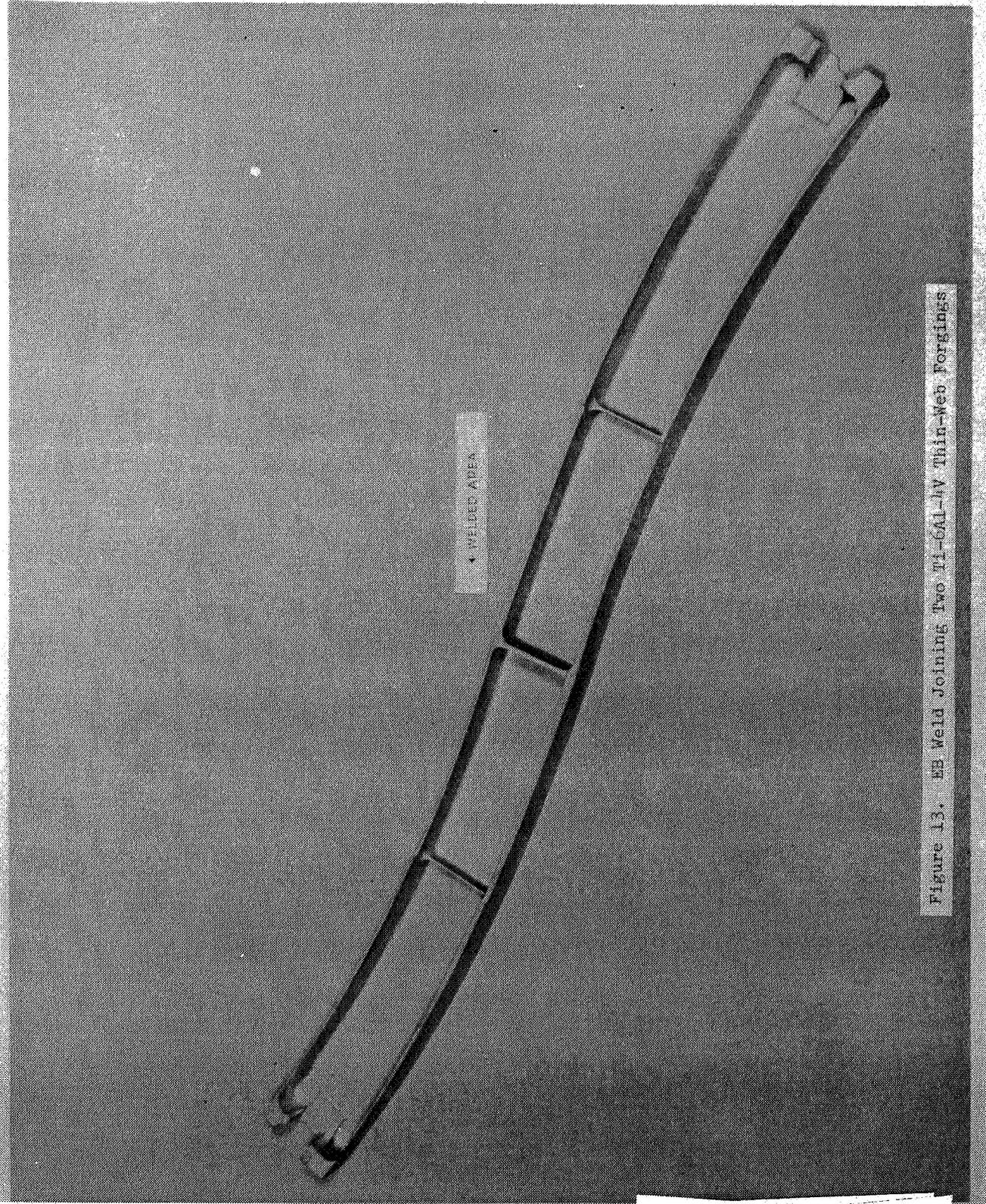


Figure 13. EB Weld Joining Two Ti-6Al-4V Thin-Web Forgings

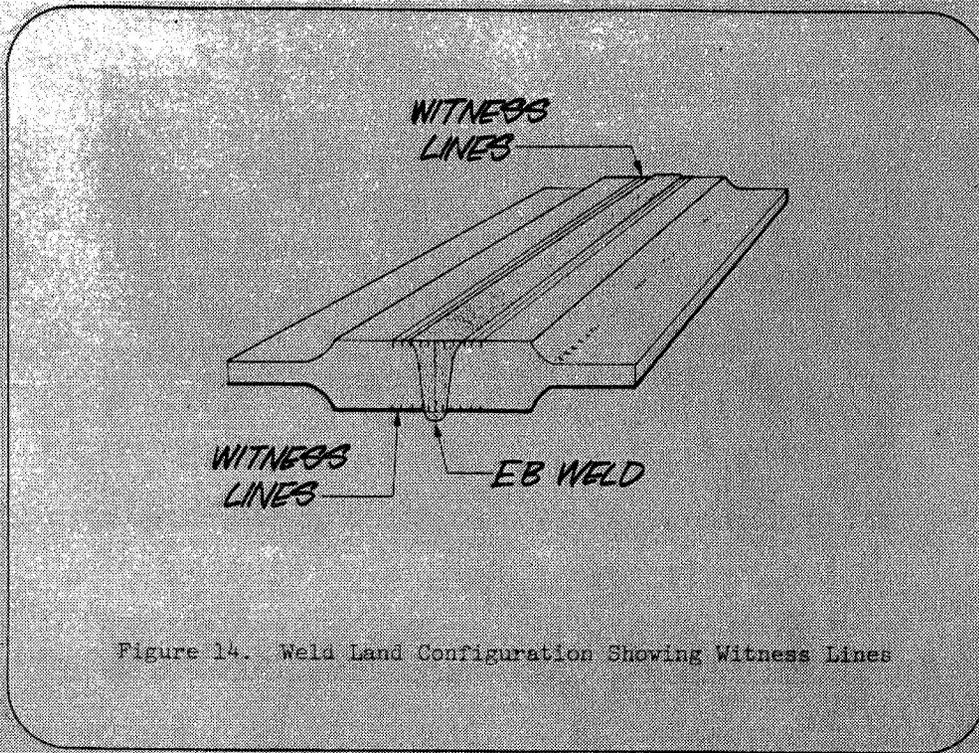


Figure 14. Weld Land Configuration Showing Witness Lines

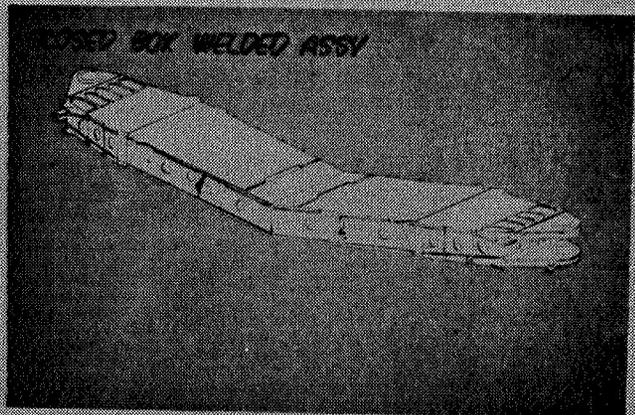
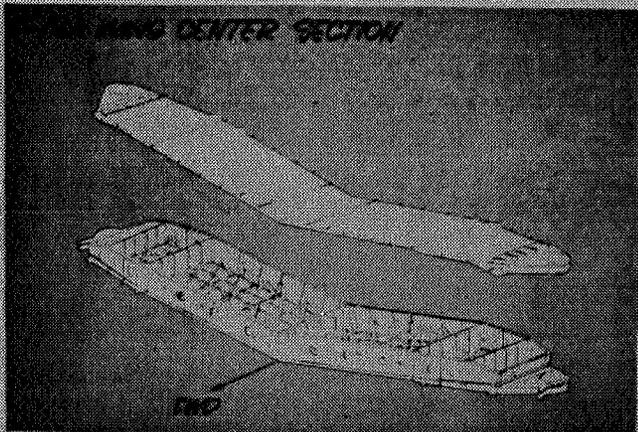


Figure 15. Schematic Representations of F-14A Wing Center Section

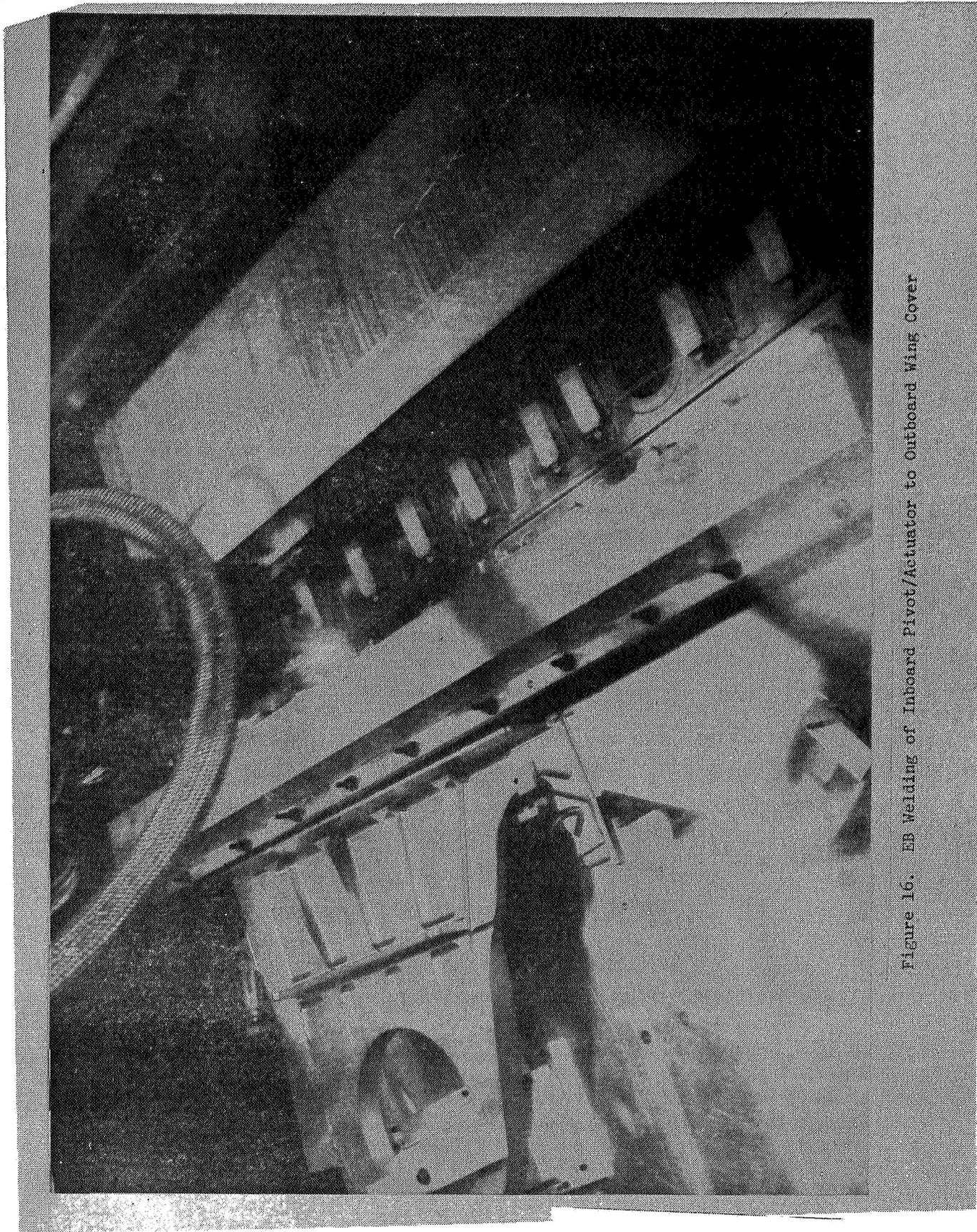


Figure 16. EB Welding of Inboard Pivot/Actuator to Outboard Wing Cover

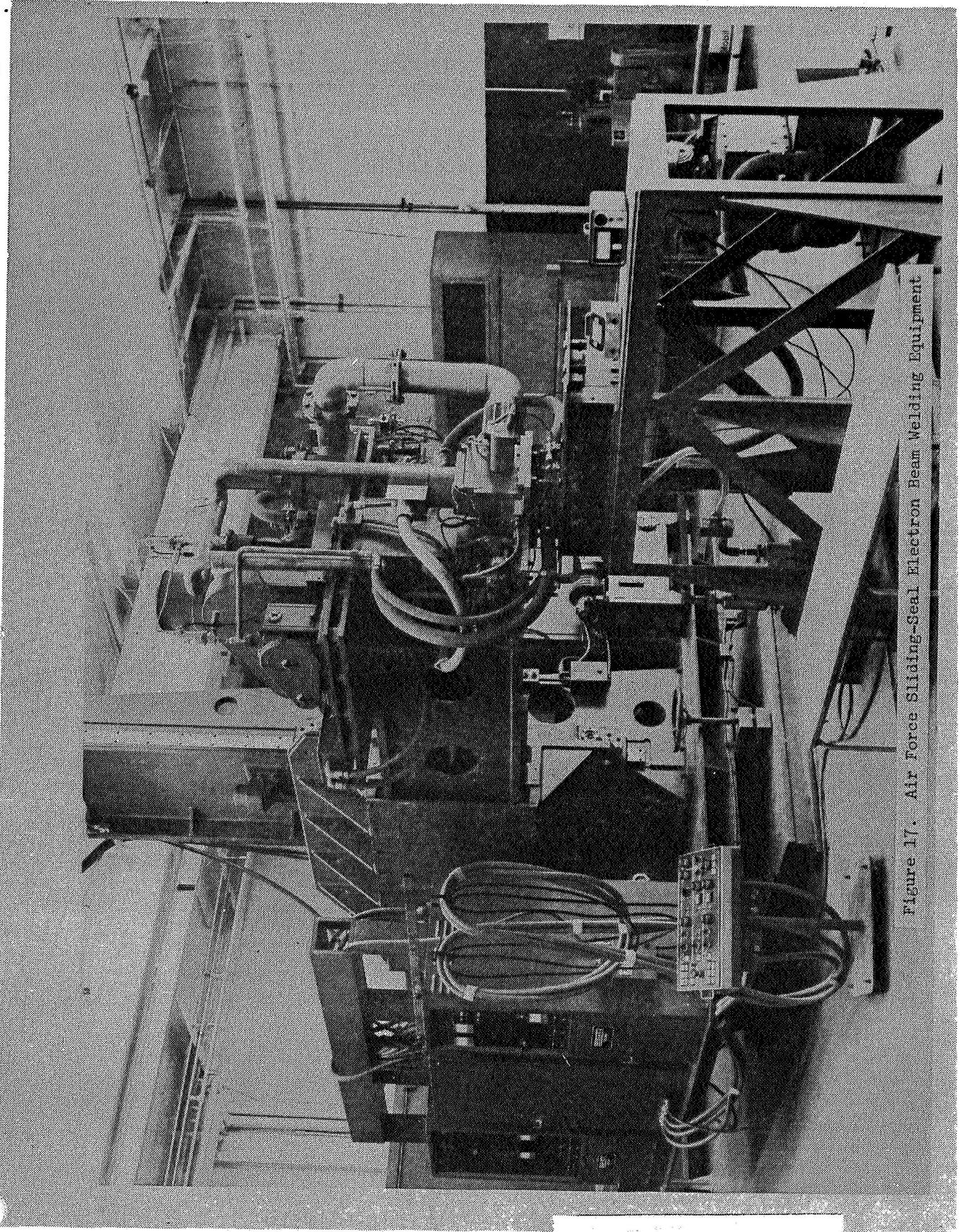


Figure 17. Air Force Sliding-Seal Electron Beam Welding Equipment

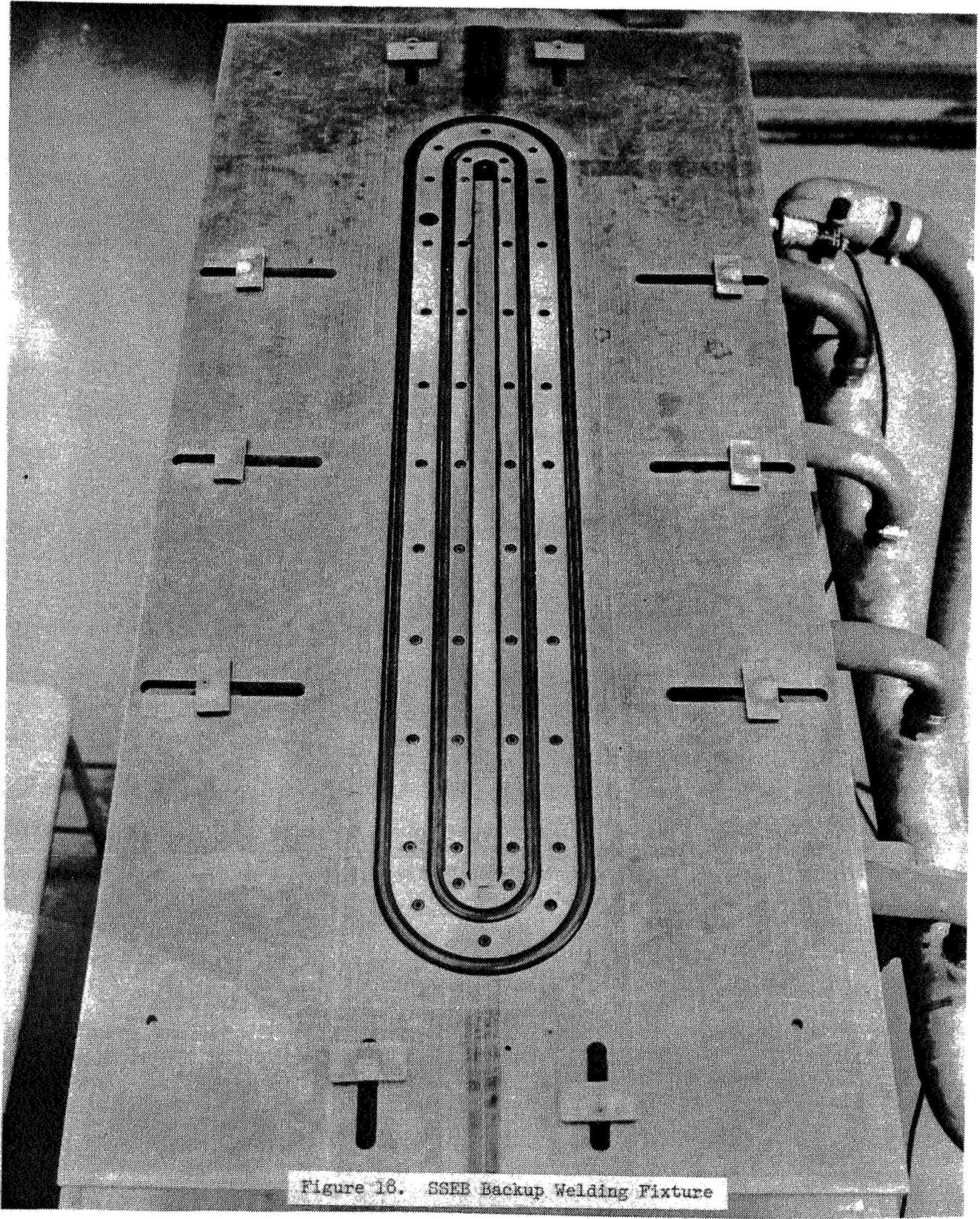


Figure 18. SSEE Backup Welding Fixture

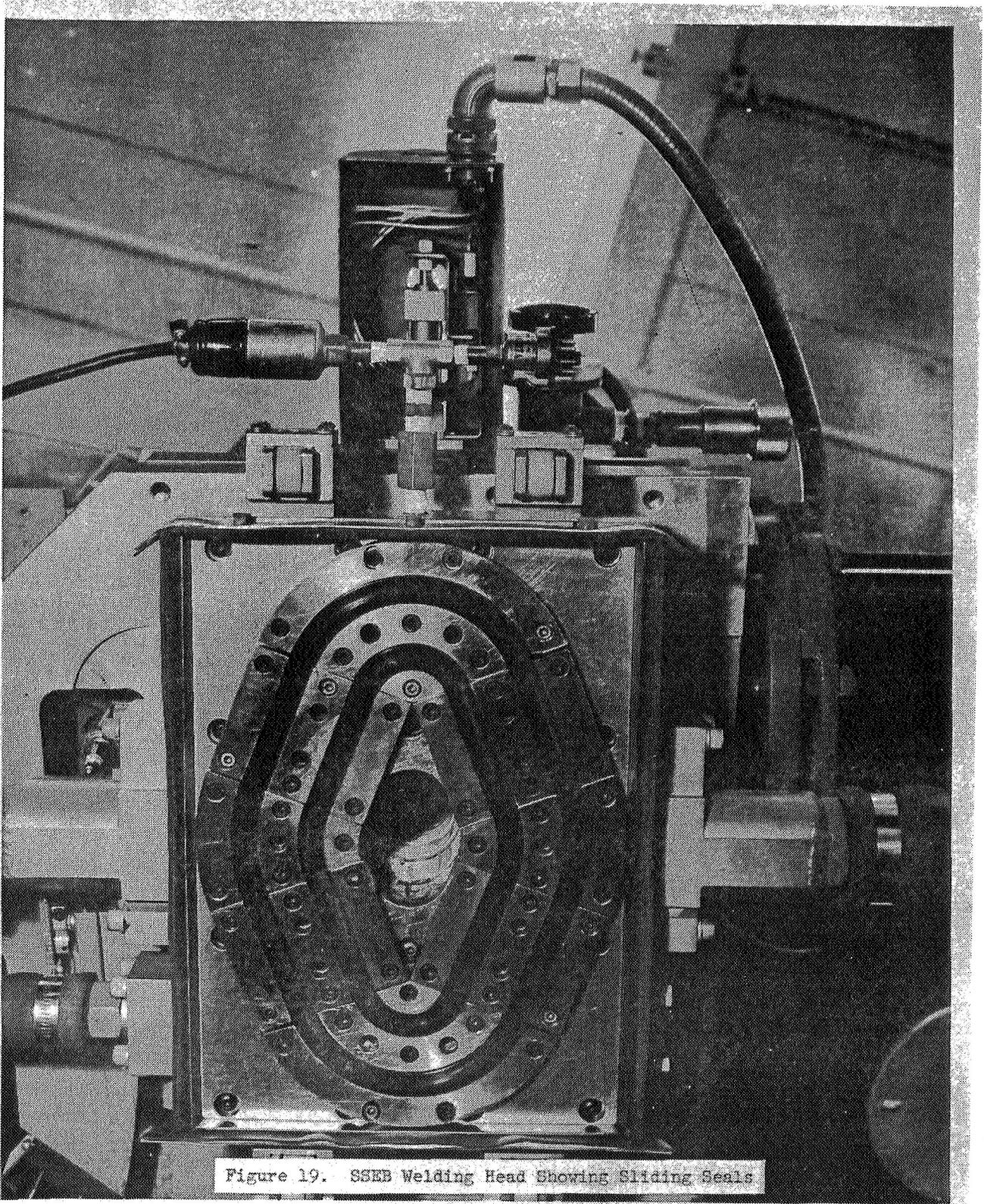
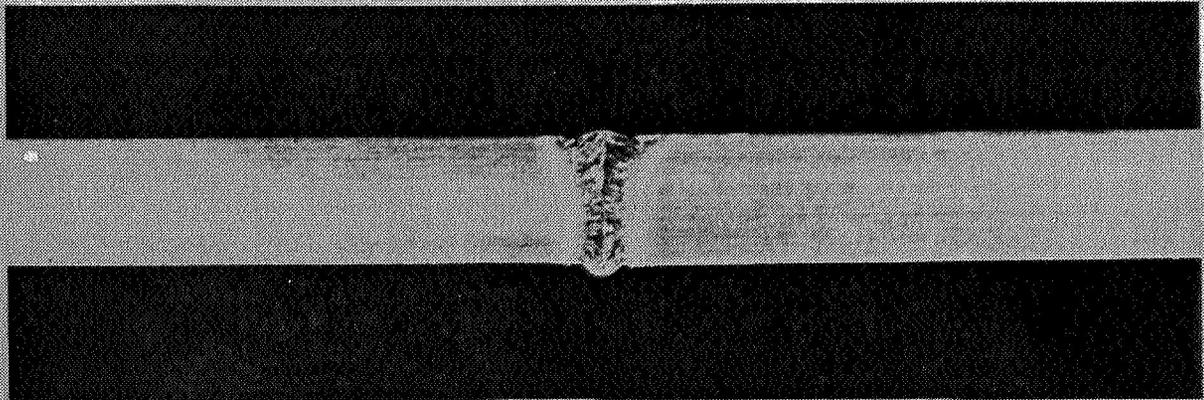
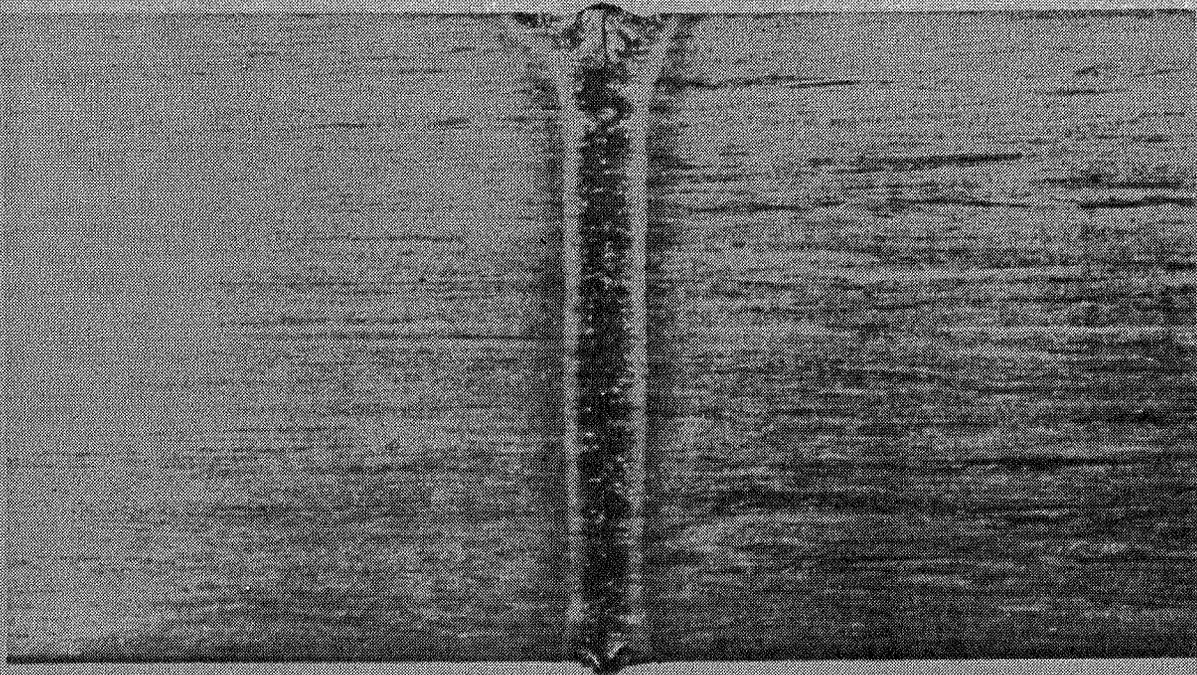


Figure 19. SSEB Welding Head Showing Sliding Seals



a. 1/4-Inch-Thick (2X MAG)



b. One-Inch-Thick (2X MAG)

Figure 20. Typical Macrostructures of SSEE Welds in Ti-6Al-4V

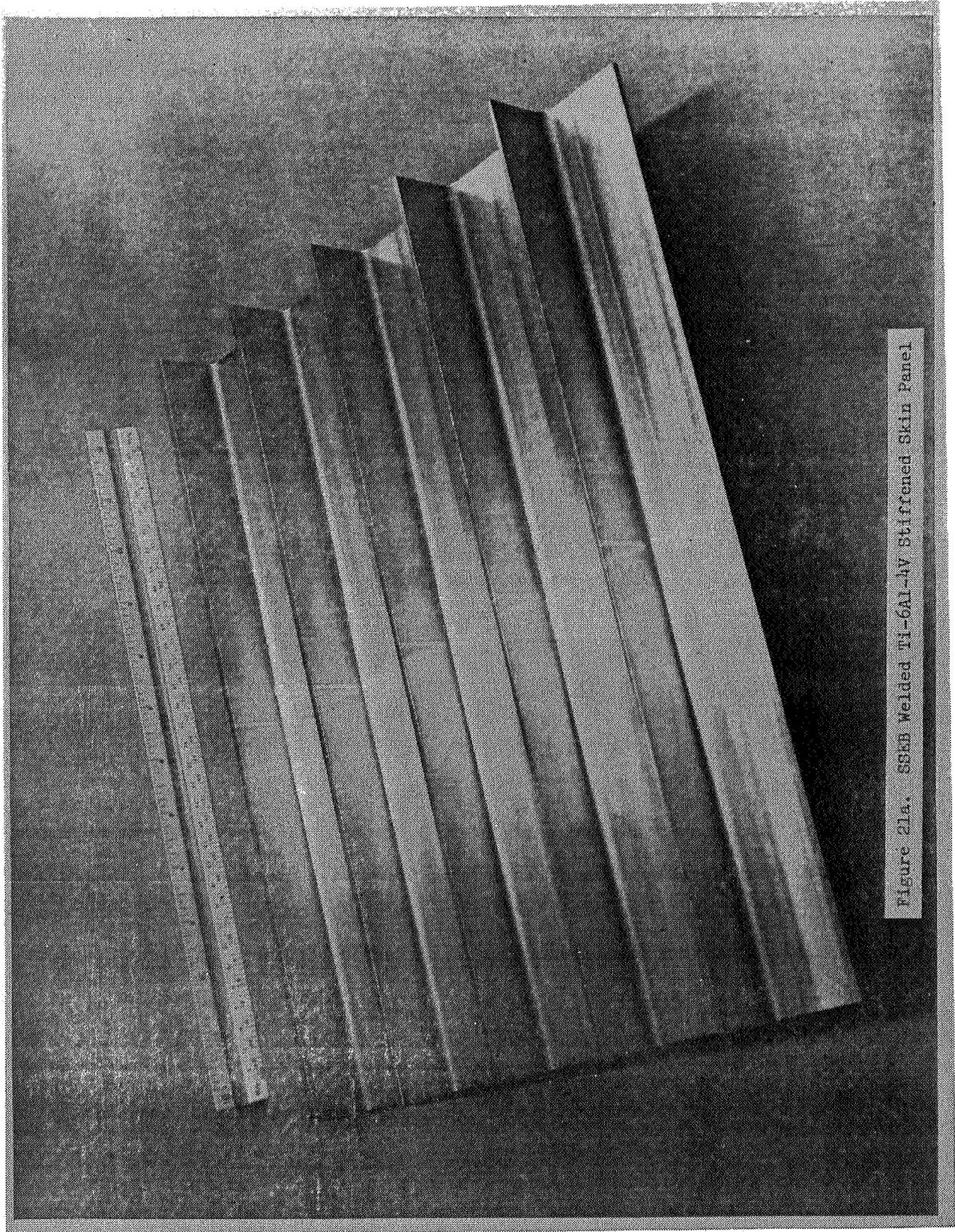


Figure 21a. S8EB Welded Ti-6Al-4V Stiffened Skin Panel

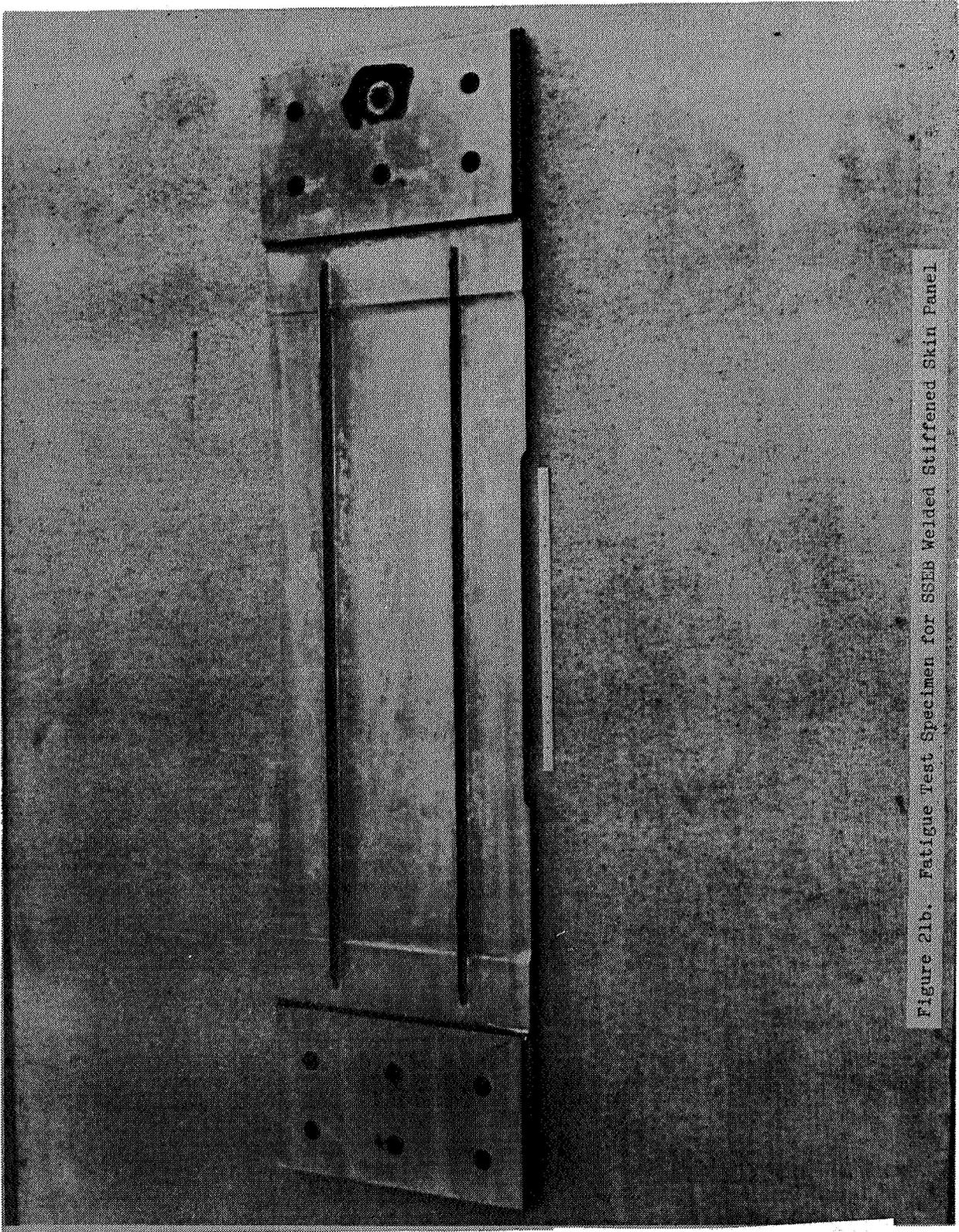


Figure 21b. Fatigue Test Specimen for SSBW Welded Stiffened Skin Panel

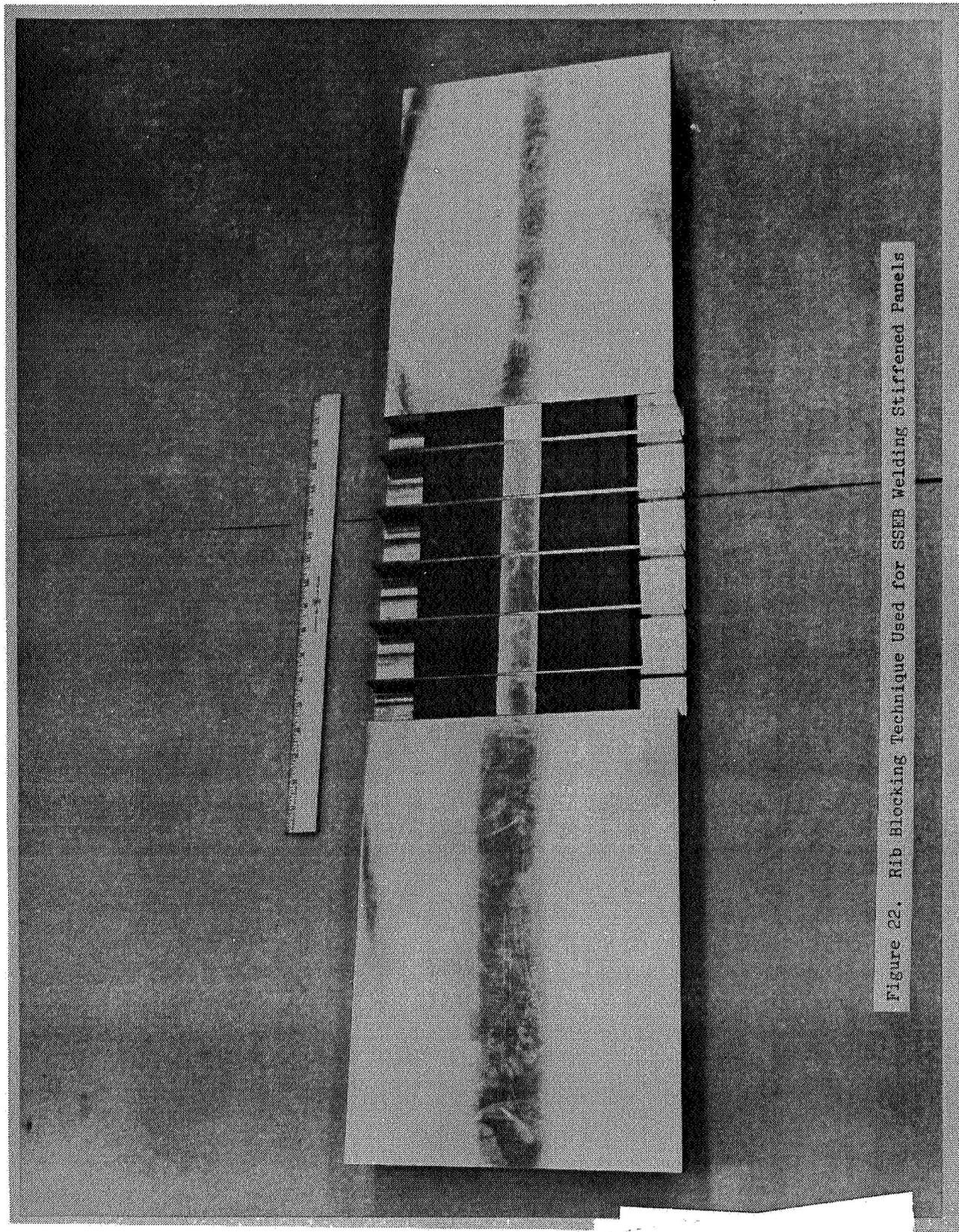


Figure 22. Rib Blocking Technique Used for SSEB Welding Stiffened Panels